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PHOTOMETRIC PROFILES OF COMETS HEADS IN MONOCHROMATIC LIGHT

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Following a review of the general facts and theories relating to comets, the author describes various methods and techniques used for their study. He then presents a detailed description of the processes used for obtaining dissociation profiles, and the various models and equations so used. Profile construction methods are reviewed and considered as mediocre because the instruments used were designed for stellar photometry and not cometary photometry. The author then describes a cometary photometer of his own design. High resolution spectra and the photometric profiles obtained from them by ordinary stellar photometers are then discussed, and various theories and hypotheses suggested.

INTRODUCTION /199*

The physical study of comets is almost entirely based on spectroscopic observations of their heads. These observations make it possible to identify the different molecules which cause the emissions and to discuss such molecular excitation processes. The recent advances in this domain, due to the use of higher resolutions, have been pointed out by P. Swings (1965) and C. Arpigny (1965).

A thorough knowledge of the processes leading to the formation of the head is still prevented today by enormous difficulties.

The detailed study of spectroscopic profiles ~~of~~ from the different bands shows us that the molecular excitation is essentially due to fluorescence. The large quantity estimates show, then, that the total gas density in cometary heads is low enough so that collisions do not have any influence, except in the central part whose radius is at most a few thousand kilometers.

On the other hand, the few, rare monochromatic photometric profiles that exist show that the gas of the head expands from a source at the center of the head. The detail of the profiles also shows that the molecule which is the cause of the emission is produced in the central part of the head, probably by dissociation of a more complex but invisible molecule, and destroyed in the external part of the head by dissociation or ionization.

The final problem we have is to reconstitute the central source which /200

*Numbers in the margin indicate pagination in the original foreign text.

we will call the nucleus, and to get as precise an idea as possible of its physical state and composition.

Regarding the first point, it now seems beyond doubt that the nucleus is a solid body containing practically the entire mass of the comet, but whose cohesion force might be very weak. The temperature of this body is an essential parameter for our problem, but depends on the detailed model that we take for the nucleus; we shall come back to this in detail in a subsequent paper. In any case, we shall calculate a temperature distribution which will essentially depend on the composition, the heliocentric distance, the surface structure and the external layers, and on the rotational movement of the nucleus. Let us point out now that the erroneous image, which is still widely prevalent, of the solar radiation striking the solid surface of the nucleus, will be discarded since it is in flagrant contradiction with the observations. In fact, a purely gaseous comet such as Burnham 1959 k, has a density of dusts in an area of about 500 kilometers around the nucleus such that the stars eclipsed by this region are notably weakened [Dossin, 1962]; also, the photometric profile of the continuum of this comet shows a positive gradient $\gg 2$ near the center [O'Dell, 1961]. From these two facts, it is possible to conclude that the optical thickness in the continuum is very large at the surface of the nucleus and, therefore, that no solar radiation directly reaches this surface.

The model for the nucleus that we shall offer, in short, shall be a Whipple nucleus surrounded by a dense dusty region with a radius of a few hundred kilometers. We shall call this part of the comet the "nuclear region", and shall define its limit as the surface for which the optical depth in the continuum equals 1.

The nuclear region itself is surrounded by a region more or less extensive, where the gaseous density is such that collisions therein play a predominant role. We shall call this region the "atmosphere" of the comet. Within this /201 region a Boltzman quasi-equilibrium exists and the atmosphere limit can be defined as the surface for which the free tangential course of a neutral molecule is equal to the distance which has to be travelled radially toward the exterior of this surface in order for the total gas density to decrease by a factor e. The atmosphere radius will vary considerably from one comet to another, and for the same comet will depend on the heliocentric distance.

A distinction must be made between the dusts of the nuclear region and the dusts which are observed in the coma and the tail of certain comets; contrary to the latter, the solid particles of the nuclear region constitute a stable part of the comet and follow the nucleus in its orbital movement, at least for the approximate duration of a passage of the comet in the internal solar system. This conclusion can be based on the fact that the photometric profile of the Burnham 1959 k comet is within r^{-7} at a distance of 13,000 km from the center of the head, whereas the spatial resolution element of the instrument used for this measure is about 10,000 km [O'Dell, 1961]. In fact, the examination of the continuum on the high resolution spectra obtained at the bent focus of the 193 cm telescope at the observatory of Haute Provence shows that the density gradient of the continuum is still large at distances of about 1,000 km from the nucleus.

It is very obvious that an expanding dust head cannot give such high density gradients. The solid particles of the nuclear region are probably different than the dusts which can sometimes be found in the coma and in type II tails by their size, the latter being the smallest particles for which movement perturbations are the strongest (recession during evaporation of adsorbed gas, radiation pressure, etc.); whereas the particles of the nuclear region would be more massive, their orbital movement is the least perturbed. In fact, we would be witnessing, in a way, the fractional distillation of the liberated solid component of the Whipple nucleus.

The nuclear region of the comet is obviously not in a state of thermic /202 equilibrium. The heat transfer is essentially done by radiation, but we also have to take into account the heat transfer by molecules diffusing through the nuclear region. It is interesting to point out at this time a few remarkable consequences that this model allows us to foresee. The molecules evaporating from the nucleus will be submitted to a large number of collisions with the solid particles before escaping from the nuclear region. If there is a temperature gradient in this region, the molecules will be accelerated in it in the direction of the positive temperature gradient. Therefore, the molecules will be injected into the atmosphere with a velocity distribution which is well determined and which is a function of the direction in which they escape. The transfer of the kinetic moment between the gaseous component and the dusty component in the nuclear region implies that the dusty component will diminish in the direction opposite to the direction of the maximum speed of escape of the gaseous component. Therefore, we can expect that the luminosity maximum of the continuum and the different bands will be slightly shifted with respect to the nucleus position. In fact, such a displacement is observed between the bands of the different molecules of the Burnham comet. The displacement which is observed is of the order of a few hundred km which is of the same order as the spatial resolution of our spectra. This observation only gives us a rather doubtful qualitative argument; on the other hand, the continuum was too weak on our high resolution spectra to be able to measure with any precision the displacement of the maximum in the continuum with respect to the maximum in the molecular bands. We can also expect that the nucleus rotation will be represented by a notable deformation of the nuclear region, since the solid particles leaving the equatorial region of the nucleus will have an initial speed of the order of a few cm/sec with respect to the solid particles coming from the polar region. Finally, we can foresee that the theories which attempt to establish the law of luminosity of a comet with respect to the distance to the /203 sun will be seen in a new light since the flux of the gaseous component produced in the nucleus will depend not only on the heliocentric distance but also on the gas and dust density in the nuclear region. We can finally foresee that the nuclear region is detectable by infrared radiometry between 9μ and 14μ or between 3.5μ and 4.2μ for a comet passing close enough to the earth ($\Delta > 0.5$ AU). The dusts of the external layers of the nuclear region will, in fact, be in radiative equilibrium and their temperature will be relative to: $T = \frac{450°K}{\sqrt{r}}$.

Such a hot body of a few seconds in diamter is easily detectable.

The problem of determining the nuclear composition is not simple. In principle, it would be sufficient to "recondense" the material detected in the head and in the tail to find the nuclear composition. In fact, not only does this process lead to multiple solutions from which we must make a difficult choice, but also, at the present time, we have only a fragmentary knowledge of the head composition due to the limited extent of the observed spectral domain. In short, we have to reconstruct a jigsaw puzzle from which an undetermined number of pieces is missing. However, we must examine in detail the pieces we have in order to clear up the problem.

We can divide the head and tail components into three main groups:

1. the dust from solid particles (head and tail)

2. the radicals and neutral atoms (head only)

3. the ions (almost only in the tail)

In the first approximation, it seems that these three groups appear and behave in independent ways. Therefore, any comet can appear to be formed by a combination of these three components in variable proportions. Examples of comets consisting of only one of the components in the pure state are known:

(1) Baade, Haro-Chavira, Schwassmann-Wachmann /204

(2) Encke, Burnham

(3) Morehouse, Humason.

These differences in composition in the spectrum do not necessarily imply a difference in chemical composition of the comet nucleus, but can be the result of various physical conditions, since the spectrum of one comet varies considerably during its passage through the internal solar system [Swings, Haser]. A statistical study of the spectra of numerous comets made it possible for these authors to determine that the heliocentric distance was the dominant parameter for the spectral evolution. Therefore, it is necessary to be sure of the composition of the comets when interpreting their spectral differences.

We must finally point out the importance of the recent identification of nebular transitions, 6300λ and 6364λ, of oxygen in the comet MRKOS [Swings and Greenstein, 1958]. It seems almost doubtless that the interdictory bands of oxygen are present in the spectra of numerous comets. [Swings, 1962]: Whatever the excitation process called upon for the formation of these bands, it seems difficult to escape the conclusion that the quantity of atomic oxygen is several times larger than the quantity of C_2 in these comets. This fact again stresses how careful it is necessary to be when one wants to deduce the nuclear composition from observations of the head.

On the other hand, it can be expected that the composition of the gas evaporating from the nucleus will be very different from that observed for the coma. In fact, this gas must first pass through the nuclear region where it stays for a relatively long time and where it is susceptible to transformation by thermochemical reactions. Then, it passes through the atmosphere where the photochemical reactions are to be found, and finally, it escapes into the coma where only dissociation and ionization remain as transformation possibilities. From this rather complex process, we can only observe a very ephemeral phase /205 which corresponds to the fact that some dissociation products have resonance transitions in the accessible spectral domain. Therefore, it is necessary to analyze the collectible data on this phase in all their detail in order to find the trace of preceding transformations.

During the analysis of these data, an initial point to determine will be an estimate of the atmosphere radius of the comet under study. For that purpose, we have two independent techniques. The first one will be to compare the spectroscopic profile of the bands at various distances from the nucleus, to the pure fluorescence profile calculated by taking into account the Swings effect. The further the observed profile is from the calculated profile, the closer we shall be to the atmosphere limit. The use of this method requires that certain conditions be fulfilled. First, we must be able to calculate the band profile. This can be done with enough certainty for CN, CH, OH, and NH if photometric recordings of the solar spectrum with very high resolution, accomplished by Migeotte and his collaborators at Jungfraujoch, are used for the calculation. Then, it is necessary to have spectra, the spatial and spectral resolution of which are sufficient. Some of the spectra we obtained at the bent focus of the 193 cm telescope at the OHP fulfill this condition well enough. Eventually, it is possible to do without the theoretical profile by comparing only the profile of the band at various distances from the comet center. The conclusions are then more qualitative and less certain. The second method is based on the following observation: outside of the atmosphere, molecules can be transformed only by dissociation or ionization. It is possible, as we shall see, to easily calculate the photometric profile resulting from these photochemical processes and their evolution with respect to the heliocentric distance for the radical observed. The deviations between profiles so calculated and observed profiles must make it possible to elucidate the atmosphere of the studied comet. The /206 limitation of this process is mainly due to the uncertainty of certain physical parameters such as the lifetime of source molecules. It is necessary to have the precise photometric profile of the various bands in the head central region, and extending as far as possible into the head.

A second subject to dwell upon shall be the reconstruction of the dissociation reactions producing the radicals which are observed in the head. Here again it clearly appears that the precise photometric profiles of the various bands and their evolution with respect to the heliocentric distance are our best chance to remain close to reality in the elaboration of the phenomenon theory.

We would like to make explicit what we mean by precise photometric profile. For this purpose, we must first calculate the profile of a radical produced by dissociation in order to estimate the sensibility of the profile form from the various parameters introduced into the calculation.

In any case, I think it is useless to further emphasize the importance of studying the photometric profiles; their importance has not been sufficiently taken into account up to now in spite of the repeated suggestions of Swings [1952; 1955; 1958].

DISSOCIATION PROFILE

Let us consider molecules of type A evaporating from the atmosphere and injected into the coma. For a first calculation, we will consider a model with spherical symmetry and observe the profile at a sufficient distance from the atmosphere so that the velocities of the molecules will be considered as purely radial. The A molecules evaporate with a maxwellian velocity distribution corresponding to the temperature T of the external layers of the atmosphere. In the coma, A molecules will dissociate according to the general diagram:

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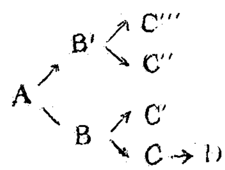

etc.

with the respective lifetimes τ_A, τ_B, τ_C, etc.

We will assume that the kinetic moment transferred during the dissociation process is negligible. This hypothesis can be justified in a few precise cases for which we have the physical data necessary for the calculation of the moment transfer: it is a question of the dissociation of H_2O into OH + H by a UV photon. The dissociation occurs for a wavelength less than 1370 Å [Kondrat'yev] and the radical OH is produced in the state $^2\Sigma$. For an incident photon whose wavelength is 1216 Å, the <u>maximum</u> impulse transmitted to the radical OH results in a recession velocity of 20 cm/sec, therefore, quite negligible in relation to the thermal velocities. The same calculation can be repeated for the reactions HCN + $h\nu \rightarrow$ H + CN and $NH_3 + h\nu \rightarrow H + NH_2$; the recession velocities found are smaller still.

Let us calculate the photometric profile of molecule C, which is the same as calculating the density of C per surface unit with respect to the projected distance ρ to the center of the head. For convenience in using the results, we have standardized the variables as follows:

the unit of length is chosen equal to $\tau_C v_M$, τ_C being the lifetime of the observed radical, and v_M the maximum velocity of the Maxwell distribution;

the unit of time is chosen equal to τ_C.

In this system, ρ will be replaced by the dimensionless variable $X = \frac{\rho}{\tau_C v_M}$ and the lifetimes τ_A and τ_B by the dimensionless parameters $a = \frac{\tau_A}{\tau_C}$

and $b = \frac{\tau_B}{\tau_C}$. Velocity will be expressed by $V = \frac{\nu}{\nu_M}$.

The volumetric density of radical C with respect to the standardized distance R to the center is expressed by:

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$$N_C(R) = \frac{N_A(R_0)R_0^2}{(b-a)R^2}\int_0^\infty F(V)\exp\left(-\frac{R-R_0}{V}\right)\left\{\frac{b}{1-b}\left[1-\exp\left(-\frac{R-R_0}{V}\frac{1-b}{b}\right)\right] - \frac{a}{1-a}\left[1-\exp\left(-\frac{R-R_0}{V}\frac{1-a}{a}\right)\right]\right\}dV$$

where $F(V) = \left(\frac{8m}{2\pi kT}\right)^{1/2} V^2 e^{-V^2}$ is the Maxwell distribution function expressed with respect to V.

$N_A(R_0)$ is the volumetric density of molecule A at a distance R_0 from the center; we shall take $N_A(R_0)R_0^2$ equal to unity.

The surface density at the distance X from the center is then obtained by integrating (1) along the line of sight; we have:

$$n_C(X) = 2\int_0^\infty N_C\sqrt{(X^2+Y^2)}\,dY \tag{2}$$

We have calculated $n_c(X)$ by numerical integration for a series of values of the parameters a, b and R_0. A few examples of these results are given in Figure 1 where log $n_c(X)$ is the ordinate and log X the abscissa. This presentation has the advantage of making easier the comparison of the studied profile within X^{-1} which represents a uniform expansion from a source point (straight line at 45°).

Let us remark that at equilibrium the photometric profile of a band outside the atmosphere is constant. In fact, if the rate of production of the source molecules changes, this corresponds only to a shifting of the profile along the ordinate axis. If the ejection velocity changes (atmospheric temperature), this corresponds to a shifting of the profile along the abscissa. A change in lifetimes τ_A, τ_B, and τ_C due, for instance, to a change of the heliocentric distance, leaves the profile unchanged since all the lifetimes vary proportionally and a and b depend only on their ratios. However, it should not be forgotten that this is true only at equilibrium; if, for instance, we have a sudden ejection of material, or if we have a rapid variation in the life- /209 times due to rapid variations of the solar flux, the photometric profile of the bands will be markedly modified.

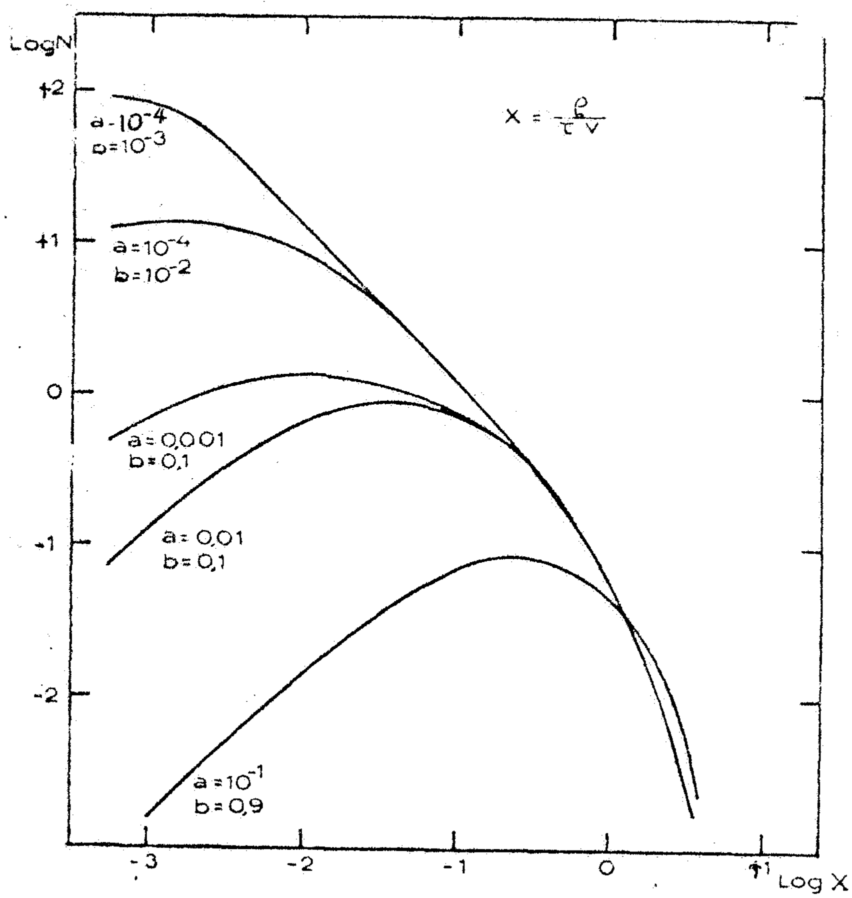

Figure 1.

The essential characteristics of these curves are always the same whatever the values taken for the parameters a and b; the influence of parameter R_0 is negligible. We have an expansion zone within X^{-1} surrounded by a production zone whose slope toward the center is > −1 and toward the outside, a destruction zone whose slope decreases rapidly. For values of parameter a > 0.1, the expansion zone disappears and the slope decreases regularly when one passes from the center to the edge of the comet. /210

We must note that these curves represent the profile for projected distances spread on more than three orders of magnitude. In practice, the profile observations seldom make it possible to have X vary more than one order of magnitude, and the observed profiles then represent only a portion of the curves presented in Figure 1. In the production zone, the profile stands out clearly from the X^{-1} profile only for the values of X close to the value of b, and for the same value of b two profiles corresponding to various values of a can be well distinguished only for values of X between a and b. Therefore, we can estimate the spatial resolution necessary to observe the formation of molecule C. The following table gives some typical values.

TABLE 1.

τ_a or τ_b \ v_M	0.1 km/sec	0.3 km/sec	1 km/sec
1/4 hr	90 km	270 km	900 km
1 hr	360 km	1,080 km	3,600 km
4 hr	1,440 km	4,320 km	14,400 km

The examination of this table shows immediately that it is indispensable to use an instrument giving a very high spatial resolution if one wants to obtain precise and significant photometric profiles. The following table gives the resolution in km that one obtains with a diaphragm of 1 mm at the Cassegrainian focus of the 200 inch telescope at Mount Palomar (2.5 seconds/mm), of the 193 cm telescope at the Haute Provence Observatory (7 seconds/mm) and of a 60 to 80 cm telescope often used for photoelectric photometry (20 seconds/mm). The resolution is calculated for four geocentric distances typical for the comet.

TABLE 2. /211

Δ(AU) \ Scale (sec/mm)	2.5	7	20
0.2	375	1,050	3,000
0.5	937	2,600	7,500
1	1,875	5,250	15,000
1.5	2,800	7,900	22,500

The comparison of the two tables show that a comet must be exceptionally near to the earth in order for photometry performed with a classical instrument to teach us something useful on the production of radicals at the center of the head.

COMETARY PHOTOMETER

We saw in the preceding section that one essential condition for obtaining good photometric profiles was to work with a very large spatial resolution. To fulfill this condition, it is necessary to use a big telescope. It is also indispensable to work with a large spectral resolution in order to separate perfectly the various bands of radicals and continuum. This quality is essentially bound to the photometer used and we will briefly analyze the techniques currently used.

First, we will cite as a reminder the profiles picked up from photographs with or without a filter [K. M. Yoss, 1953; F. D. Miller, 1955, 1960, 1961; K. Wurm and B. Balazs, 1963]. This process accumulates the disadvantages inherent in photographic photometry in general (small dynamic scale, calibration difficulties, nonreproducibility and imprecision in the measurements) and the fact /212
that the passing band is always enormous and badly defined. Therefore, one establishes laboriously the inaccurate profile of an indefinite mixture of various bands and of the continuum. These profiles, therefore, are completely useless and good photographs of the comet will only serve to verify the symmetry of the coma on the total image.

We obtain initial improvement by using a photoelectric photometer with colored filters, but the spectral resolution so obtained does not make it possible to separate the share of the different bands from the share of the continuum. [M. F. Walker, 1958; R. Bouigue, 1958; D. Malaise, 1962; P. Mianes, 1958; W. M. Sinton, 1959].

Final improvement consists only in replacing the colored filters by interferential filters [M. Schmidt and H. Van Woerden, 1957; C. R. O'Dell, 1961; C. R. O'Dell and D. E. Osterbrock, 1962; W. Liller, 1961]. But these filters always have rather large wings (brims) which sometimes necessitate fairly important corrections to the observed profiles. Apart from this source of error and imprecision, we must point out that this technique only allows the study of one band at a time, but rather frequently we have only a limited time for the observation of a comet. Therefore, we will have to be content with the study of only one band and the adjacent continuum for each night of observation or we will have to make up our mind to lose time and data in order to change the filters. In the first case, we sacrifice deliberately one of our best sources of data, i.e., the comparison of profiles of different bands at the same time and their relative evolution with respect to time. In the second case the accuracy of each profile which is roughly proportional to the duration of the measurement will be inversely proportional to the number of bands studied. Moreover, we will never be sure that the profiles of various bands correspond exactly to the same spot on the comet. Therefore, it will not be possible to detect an eventual displacement of the maximum of the various bands studied.

In practice, one customarily took the profile not by letting the comet /213 image narrowly pass on a small diaphragm constituent, the resolution element, but by measuring the flux through diaphragms of various diameters centered on the comet. This technique has the advantage that one has to measure a current nearly proportional to the diaphragm diameter, so that there is no accuracy loss when one measures the regions where the luminosity per surface unit becomes weaker and weaker. This advantage is counter-balanced by numerous disadvantages: we must make an additional unwinding in order to calculate the density. We must assume that the coma has a circular symmetry. The maximum diameter of the diaphragm is strongly limited by the eventual presence of stars in the field. For each diaphragm, a different region of the filter is used. Finally, in practice, we must limit ourselves to 5 or 6 apertures. Obviously, with such a small number of points, it is only possible to have an extremely vague idea of the photometric profile.

If we add to the preceding remarks that photoelectric photometers are traditionally used at the Cassegrainian focus of small telescopes, we must admit that all the conditions for obtaining mediocre profiles according to the standards we just established have been scrupulously followed. It seems that this comes mainly from the fact that comets, in most cases, are only occasional objects of study, and that instruments normally designed for stellar photometry are then slightly modified for cometary photometry.

The importance and the specificity of the subject requires that a specialized instrument for the study of photometric profiles of comets be constructed. Therefore, we undertook the construction of a cometary spectrophotometer, a brief description of which follows:

The instrument is in the form of a concave network spectroscope whose source is a diaphragm with a circular aperture placed at the focus of the telescope (F = 15). The dispersive constituent is a fixed concave network with /214 a curvature radius of 750 mm*. This network has a surface area 45 mm by 65 mm engraved with 982 lines per mm, and a blaze angle of 18°03'. The bands for study are selected by a series of mobile and adjustable slits on a Rowland circle. The photomultipliers, type ASCOP 541 A 05 M, are placed behind the slits between the sagittal and tangential focal lengths of the network. We use the Paschen setting with an incidence angle of 32°25'. Under these conditions, the light corresponding to the blaze is diffracted at an angle of 3°41' and corresponds to 6200 Å in the first order and to 3100 Å in the second. This setting was especially conceived to facilitate the study of NH_2 (in the region of 5720 and 6640 Å), NH (in the region of 3370 Å) and especially OH (in the region of 3100 Å).

The bands corresponding to wavelengths between 4050 (C_3) and 6640 (NH_2) are studied in the first order and those between 3100 (OH) and 3880 (CN) in the second order. Hence, the extreme diffraction angles are +13° (CN) and −8° (C_3). This system has the advantage of giving practically constant astigmatism for

*Bausch and Lomb, no. 35-52-15-64.

the spectral region under consideration [Beutler 1945; T. Namioka, 1959]. The dispersion of the instrument is 14 Å/mm in the first order and, of course, 7 Å/mm in the second. The inlet diaphragm diameter is fixed at 1 mm in principle but according to the brilliance of the studied object, other better-suited dimensions can be used.

The inlet diaphragm is placed at the center of a large diagonal mirror. From there, the field image is carried in the plane of a reticle where it can be observed during the measurement by means of a slightly magnifying (to large field) ocular. This system of vision permits rigorous alignment during the measuring. A marking system makes it possible to record brief signals on the recordings in order to mark the passage of the center of the comet on the distance reference marks of the reticle. The sweeping is performed by means of the slow corrective movement during straight line ascension of the telescope. Since we work with 6 channels at the same time, the commutation sensitivity /215
of the electrometers will be automatically ensured by small logic systems accomplished with microcircuits. The instrumental profile of the spectrophotometer is excellent as can be seen on the few examples given in Figure 2. It must also be noted that the cutoff wavelengths of each band can easily be adjusted to within ±1 Å of the value. The adjustment and its check will be made easily and quickly by illuminating the inlet diaphragm with a source which gives calibration lines on the front side of the slits. The slits will then be positioned with respect to these lines with the desired accuracy.

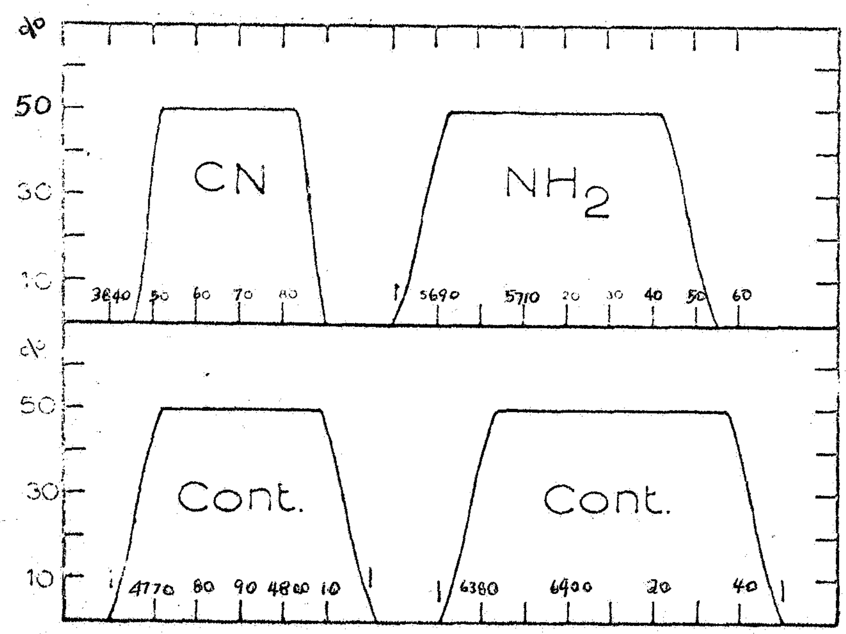

Figure 2.

In order to estimate the performance of the apparatus, we made an approximate calculation of its detection ability. First, let us define a series of characteristic parameters:

$Q(\lambda)$ is the total quantum efficiency expressed as the number of photoelectrons emitted by the photocathode per photon of wavelength λ incident outside /216 the earth's atmosphere. The numerical values of this parameter have been calculated for a dry air mass Z = 2 according to the Allen tables, taking into account the quantum efficiency of the photomultipliers, a 50% efficiency of the network, and an 80% reflectivity of the mirrors.

A list of bands selected for the study of moderate emissions and background are given in Table 3. The cutoff wavelengths indicated are exclusive for the bands in the continuum and inclusive for the molecular bands. Six of these bands can be studied simultaneously. It can be seen that it is considered very important to obtain precise spectrophotometric profiles of the background. Moreover, the apparatus will serve to study, carefully and quantitatively, star eclipses by the nuclear region.

TABLE 3.

OH	3077	3160	C_2	4667	4737
NH	3349	3374	cont.	4748	4837
cont.	3585	3673	C_2	5112	5167
CN	3850	3884	cont.	5184	5280
cont.	3910	3948	cont.	5637	5700
C_3	4010	4077	NH_2	5700	5743
cont.	4140	4178	cont.	6413	6466
CH	4295	4315	NH_2	6592	6621
cont.	4384	4474			

The cutoff wavelengths of the different bands have been chosen with reference to the lists of wavelengths given in the Atlas of Representative Cometary Spectra (P. Swings and L. Haser) and from the more complete list of lines detected in the high resolution spectra of the MRKOS 1957 d comet (A. Stawikowki, 1962, and A Woszczyk, 1962). These bands are given only as a guide and can always be adjusted for the particular spectral characteristics of the comet studied. Another advantage of the spectrophotometer over a photometer with interferential filters can thus be seen.

λ	3000 Å	3400 Å	4000 Å	5000 Å	6000 Å
$Q(\lambda)$	$2{,}6\ 10^{-4}$	$6{,}1\ 10^{-3}$	$1{,}66\ 10^{-2}$	$3{,}21\ 10^{-2}$	$1{,}5\ 10^{-3}$

s = detection ability of the amplification system expressed in photoelectrons per sec.

F = relative aperture of the telescope (f/C).

A_b = number of transitions per second per molecule in band b up to 1 A.U. of the sun.

Δ = distance from the earth to the comet.

$N(r) = N_0(r_0/r)^2$ = volumetric density of the emitting molecule at distance r from the center of the head, expressed as a function of the density N_0 at distance r_0 according to the law of a simple expansion.

$n(x) = N_0 r_0^2/x$ = surface density of the comet at the projected distance x from the center of the head; n(x) is simply the integral of N(r) following the line of sight cutting the comet at distance x from the nucleus.

a = radius of the inlet diaphragm of the photometer in cm.

Assuming that a is small enough for n(x) to be constant on the entire surface corresponding to the projection of the diaphragm on the comet, assuming also that the distance from the earth to the comet is much larger than the diameter of the comet, the number of electrons emitted per second by the photocathode when the diaphragm is centered at distance x from the center of the head will be:

$$i = n(x)\, A_b Q(\lambda)\, \frac{a^2}{16F^2} = N_0 A_b Q(\lambda)\, \frac{\pi^2 a^2}{16F^2} \frac{r_0^2}{x}$$

Evaluating this current at the minimum detectable current s, one obtains an expression for the minimum density N_0 that the comet must have at a distance r_0 in order that it can be detectable as far as the projected distance x. /218

$$N_0 = \frac{16\, F^2 s}{\pi^2 a^2 Q(\lambda)\, A_b} \frac{x}{r_0^2}$$

Putting in this expression $x = r_0 = x_M$, we obtain the minimum density that can be observed as far as the distance x_M from the nucleus (expressed in cm).

$$N_m = \frac{16\, F^2 s}{\pi^2 a^2 Q(\lambda) A_b} \frac{1}{x_M} = 1{,}62\, \frac{F^2 s}{a^2 Q A_b} \frac{1}{x_M}$$

The following table gives the values of A_b that we used for the numerical calculation [Arpigny, 1965]:

Molecule	λ	A_b (sec^{-1})
CN (0-0)	3883	0.100
C_2 (1,0 + 2,1 + 3,2 + 4,3)	4700	0,015
C_2 (0,0 + 1,1 + 2,2 + 3,3)	5160	0,025
C_2 (0,1 + 1,2 + 2,3 + 3,4)	5500	0,010
OH	3100	0,001
NH	3360	0,012
CH	4300	0,030

Therefore, assuming that one can measure a cathode current of 500 e/sec and working with an inlet diaphragm with a 1 mm diameter, one finds that the minimum number of molecules per cm^3 detectable at 40,000 km from the nucleus is:

CN	C_2(1–0)	C_2(0–0)	C_2(0–1)	OH	NH	CH
0.11	0.35	0.18	1	146	2.4	0.23

Burnham*	Date	Δ(AU)	r(AU)	Spectral resolution (Å/mm)	Spatial resolution (km)
V 86	4/23/60	0.240	0.935	19.5	400
V 88	4/25/60	0.225	0.950	19.5	350
V 96	4/27/60	0.205	0.987	19.5	300
U 88	4/28/60	0.209	0.999	39	1000
U 91	5/01/60	0.245	1.055	39	1200
Ikeya					
V 927	3/03/63	0.690	0.745	19.5	1000
V 964	3/13/63	1.035	0.660	19.5	1600

/221

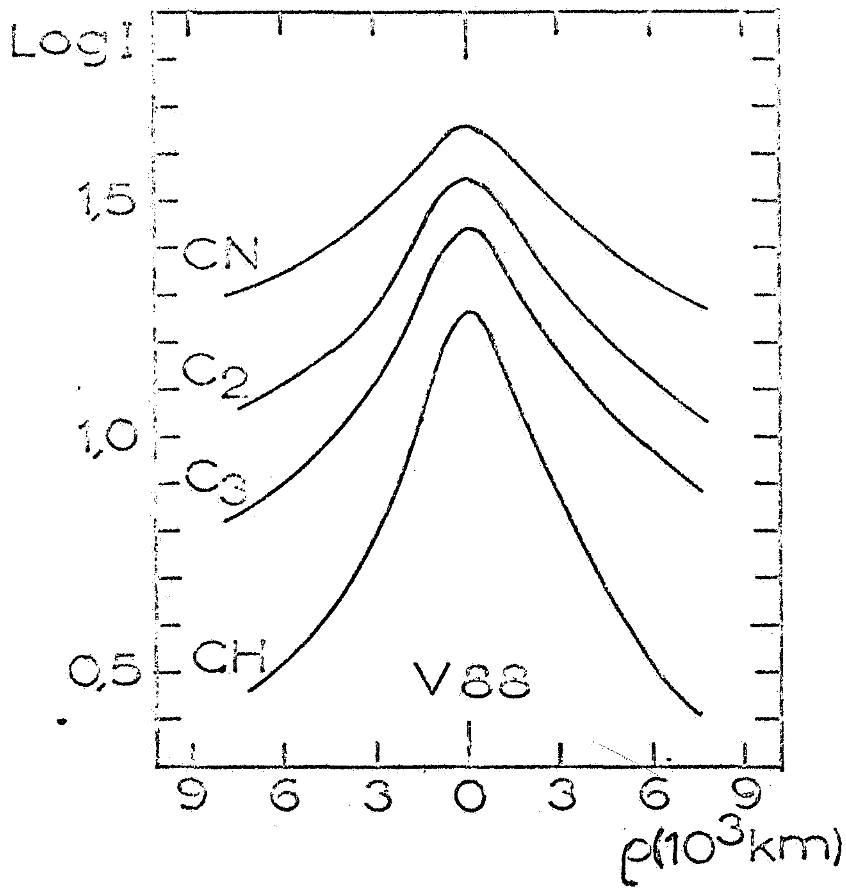

Figure 3.

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*See also Dossin et al., 1961.

Figure 3 presents the profiles of four bands which were measured on the V 88 spectrum of the Burnham comet. The scale of the ordinate represents the logarithm of the intensity in arbitrary units, the scale of the abscissa, the distance to the center in km. On this figure, the various bands have been placed so that their maximums coincide, the various bands having been independently recorded.

The examination of the figure shows immediately and in a quantitative way considerable profile differences. The gradient of the bands increases when we pass successively from CN to C_2 to C_3 to CH.

In order to compare the various bands of the same comet and their evolution with respect to time, we present all the profiles recorded up to now in Figures 4-8.

/222

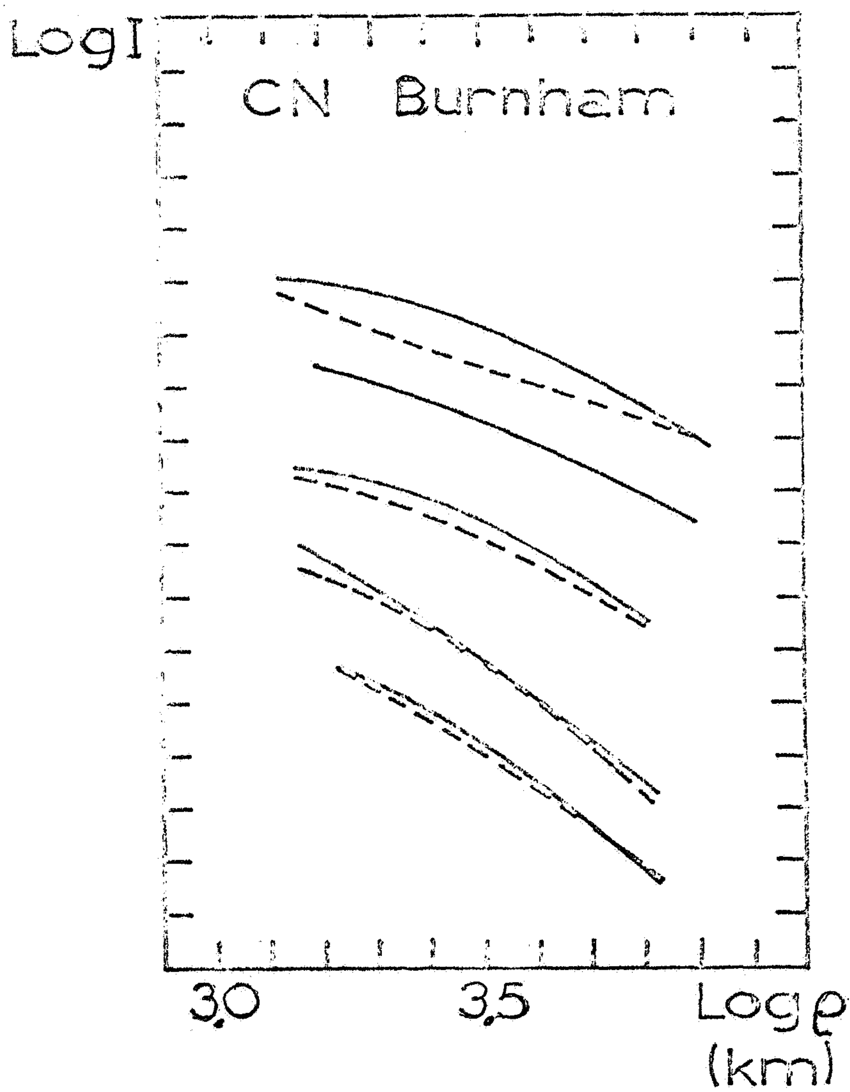

Figure 4.

The distance scale is now logarithmic. We immediately observe that the spectra used can only give the head profile in a very limited region: 0.7 to 0.9 on the logarithmic scale. This is the main disadvantage of this technique and prevents making a detailed comparison of the observed profiles and of the

/223

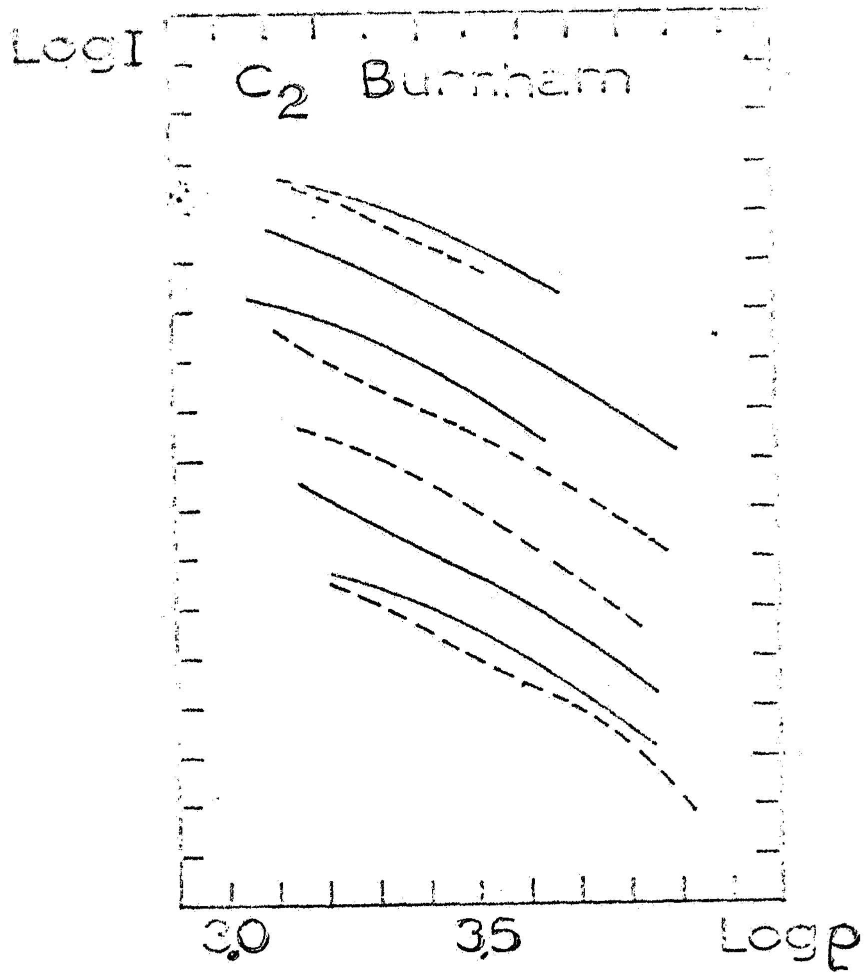

Figure 5.

dissociation profiles presented in the first section. A second disadvantage of this technique is that it requires an enormous amount of work: the few profiles we present here required the measurement and reduction of more than eleven thousand individual lines. One of the main advantages is the great accuracy which can be reached. Each profile is traced from about forty points and the mean error is not greater than 4 to 5 times the thickness of the lines used in the graphical presentation. In fact, for a band presenting numerous /224 lines, like C_2, the accuracy is only limited by the systematic deviations of the individual lines from the average profile.

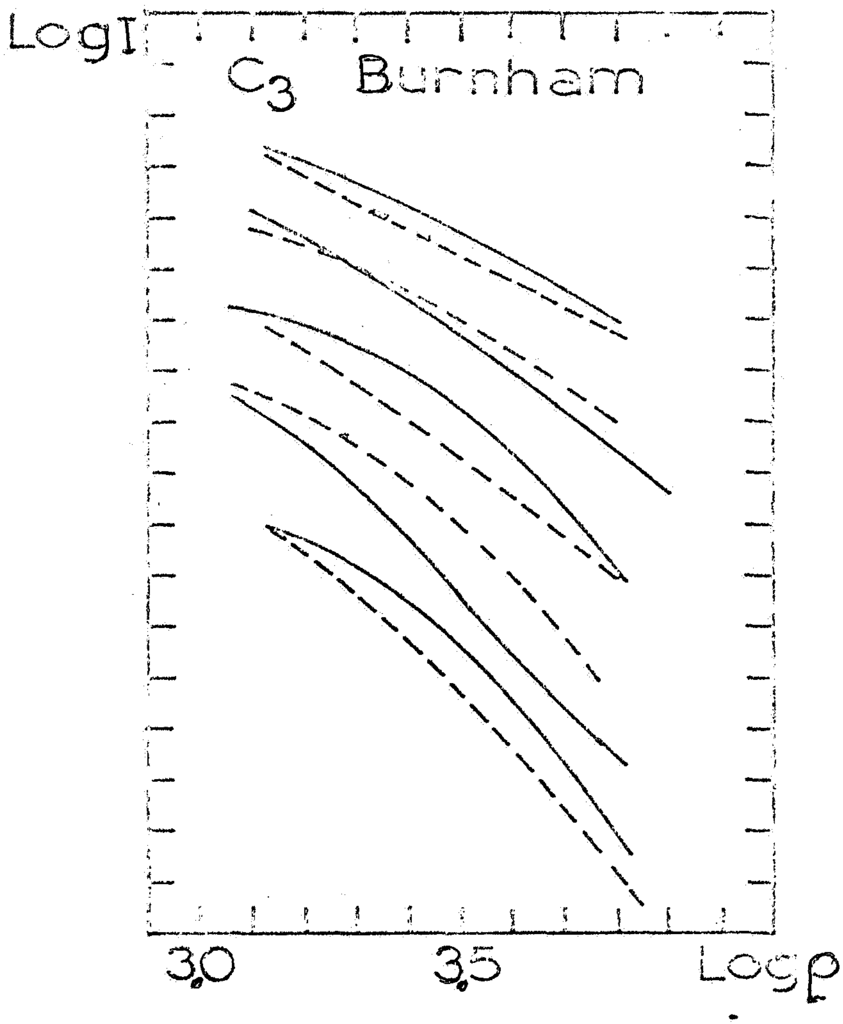

Figure 6.

The Burnham comet profiles are presented in Figures 4 to 7, by the band, and for each band in the order of increasing heliocentric distance, i.e., for each band the profiles are presented from top to bottom in the order: V 86, V 88, V 90, U 88 and U 91. The full line and the dotted line represent the profiles on each side of the center of the head for the same band and the same spectrum. /225

Since we have only studied two spectra up to now for the Ikeya comet, all the profiles are grouped in Figure 8. The C_3 profile of V 964 is missing because this spectrum is unfortunately broken in the middle of the 4050 group. /226

If we compare the profiles of the Burnham comet from the point of view of symmetry, we see immediately that CH is remarkably symmetrical and that the CN

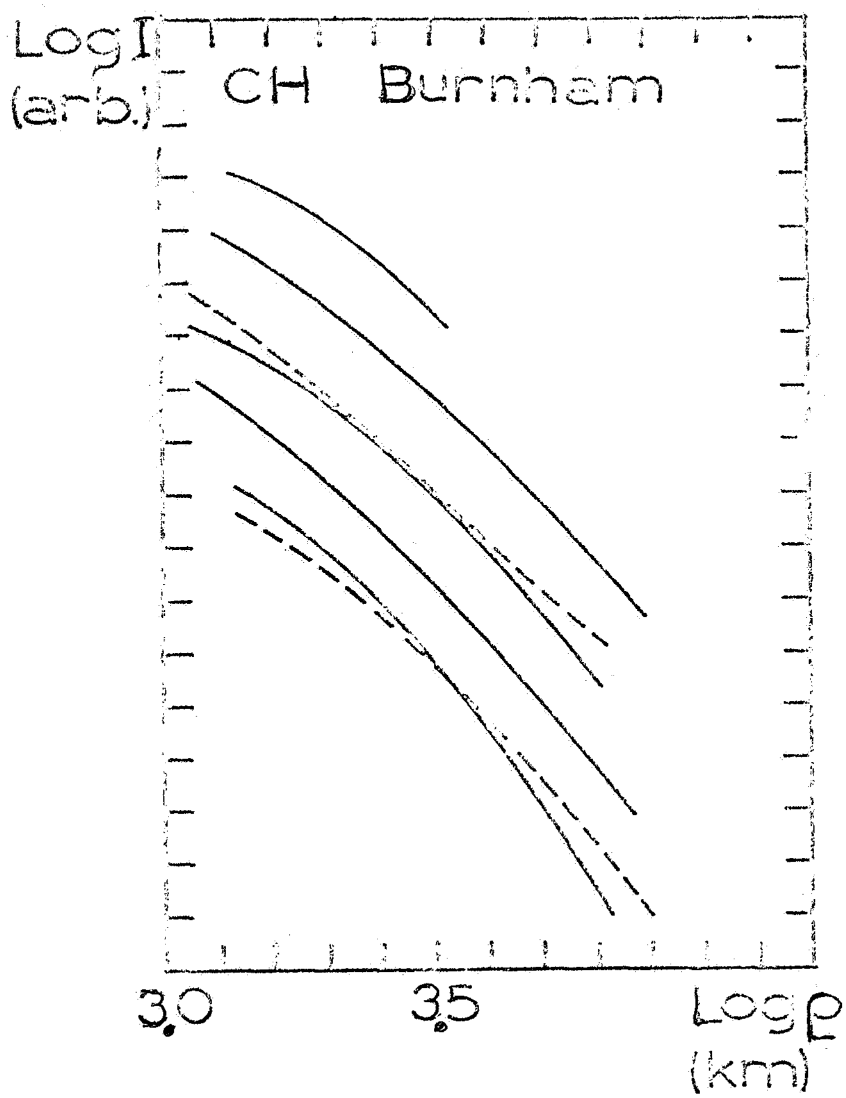

Figure 7.

dissymmetry is small except for V 86. It is quite different, however, for C_2 and C_3 which are almost always very dissymmetrical. The most interesting /227 fact to note, however, is the remarkable parallelism between the profiles of these two radicals. On the other hand, if we consider the evolution of the average gradient* of each band, it seems that the CH and C_2 gradient do not change whereas the C_3 and CH gradient have a tendency to increase when the

*We call the "gradient" of a band the slope of the logarithm curve I with respect to logarithm ρ, whose sign was changed.

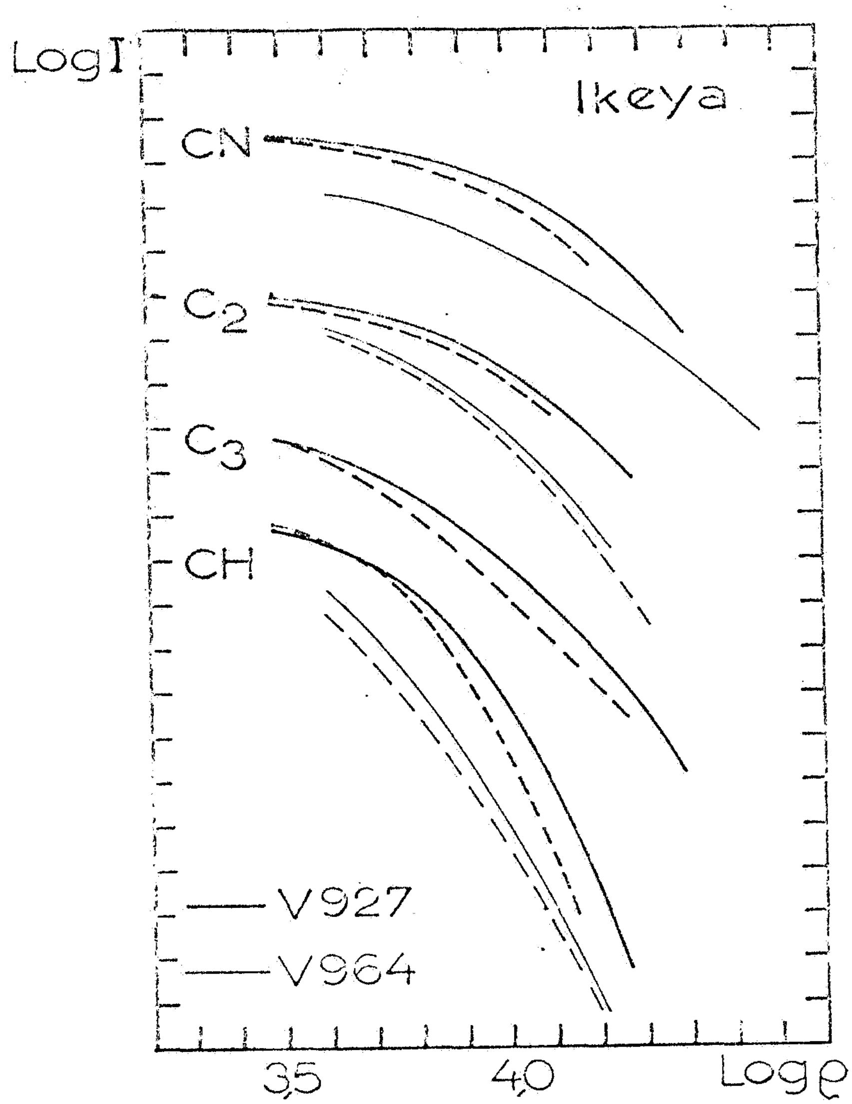

Figure 8.

comet moves away from the sun. For the Ikeya comet, it is not yet possible to compare the band symmetry because we measured only two spectra, but a comparison with the Burnham comet is interesting. We see that the CN and C_2 profile gradients are clearly smaller for Ikeya. C_2 and CH profiles are identical for V 964 and Burnham but the profiles of these two radicals show a clear deviation when we go from V 964 to V 927.

We do not want to draw premature conclusions from such limited observation material. We still have two spectra from the Burnham comet and a few spectra from the Ikeya and Seki-Lines comets. We would also like to get spectra from the same comets from which other great observatories have gathered spectra in order to have a series that is as complete as possible.

However, we would like to end with the few following remarks. The strong profile dissymmetry we observed for some radicals cannot be attributed to an optical depth effect in this case [Arpigny, 1963]. This effect should be distinguished as systematically stronger for the bands having the highest absolute intensity. The effect should even be different inside the same band if we observe a line or a group of lines which are intense (the head of branch P of CN for instance) or a line of low or average intensity (for example, an isolated line of branch R). However, we do not have that and we see that in the Burnham comet C_2 and C_3 are very dissymmetrical, whereas CN which is much more intense is almost symmetrical as well. Furthermore, this dissymmetry is far from being constant; it varies from one day to another. It seems that the dissymmetry /228 we observe here is due to a variation of the material density in the comet. Besides, these variations are small, never reaching a coefficient of 1.5. We must note, however, that all the material along the line of sight is observed and, since the spectra have been taken without a field rotator, we observe the average of a sector of the comet which can reach an opening of 90°. Variations in local density, therefore, can be much more important. In any case, these density variations are related to a variation in the production of the observed radicals. The striking parallelism between the behavior of C_2 and C_3 from this point of view seems to indicate that the production of these two radicals is bound but still independent of CN and CH production.

If we examine the slopes of the various profiles, we realize that we are either beyond or just at the limit of what we called the expansion zone. The CH band is an important exception to this rule because in all cases the profile slope of this band reaches values less than -1. Also, it seems that for this band the production zone and the destruction zone overlap, which would mean that $b_{CH} > 0.1$. From as much as we can judge from the small portion of the profile that we measured, it seems that for CH, $\tau_C v_M \approx 10^4$ km. With an expansion speed of the order of 0.5 km/sec, this gives $\tau_{CH} \approx 10^4$ sec and for the source molecule of CH, 10^3 sec $< \tau_B < 10^4$ sec.

The average slope of the CN profile goes from -0.35 for V 86 to -0.46 for V 88 and reaches -0.76 for U 88 and U 91. At the same distance from the nucleus, for Ikeya the slope is only -0.15 but becomes asymptotic to -1 for distances on the order of $10^{4.6}$ km.

The C_2 profile slope from Burnham is nearly constant and of the order of -0.6. For V 964, the slope is also -0.6 at a distance of $10^{3.6}$ km from the center, but it reaches the value -1.3 at $10^{4.2}$ km from the nucleus. Whereas for V 927, the slope starts from a much higher value (-0.17) and goes asymptotically to -1. /229

The C_3 profile slope in Burnham goes from -0.53 (V 86) to -0.71 (V 88 and V 90) to -1 (U 88 and U 91). For the Ikeya comet, the slope goes from -0.42 in the $10^{3.6}$ km region to -1 in the $10^{4.3}$ km region.

The fact that the gradient in the CN and C_3 bands seems to decrease constantly when the comet approaches the sun is in complete contradiction with the model which is based on the dissociation equilibrium. If, in the model, the gradient of a band decreases at a given distance from the center, it means that $\tau_C v_M$ increases. Now it is probable that the lifetime of a radical is proportional to the square of the distance to the sun, and that the speed of evaporation is inversely proportional to the fourth root of this distance. Therefore, the band gradient should increase when the distance to the sun decreases.

At first there are only two ways of showing this contradiction. The first is to assume that the rate of evaporation of the source molecules varies fast enough with time so that relation (1) is no longer valid. The second is to assume that we do not have a pure dissociation equilibrium but that some radicals (or their source molecules) are formed by association in the atmosphere of the comet.

In the first hypothesis, we can separate the variation, $N_A(R_0)$, with time into two components; a small and continuous component corresponding to the fact that the rate of evaporation certainly increases when the comet approaches the sun; a discontinuous and erratic component corresponding to the fact that matter is sometimes emitted in an eruptive way. The first component certainly cannot account for our observations as it would mean an increase in the band gradients for a comet approaching the sun and a decrease for a comet moving away, with respect to the gradient given by relation (1). However, the Ikeya comet was approaching the sun whereas Burnham was moving away from it, and /230
the observed effect is in the same direction for both comets. In regard to the second component, it would be very astonishing if it would give an effect always in the same direction and which would seem to vary continuously with the heliocentric distance even when different comets were compared. The second hypothesis seems more plausible. It is certain that the gas density in the comet's central region increases when it approaches the sun. The comet atmosphere, therefore, will increase its diameter and, if some radicals or their source molecules are formed by association, the closer the comet is to the sun the further their production zone will extend. The main difficulty with this explanation is that the zone of production of a radical must coincide by association with a zone where collisions are numerous. If this zone can be found on our spectra as far as distances of the order of $10^{3.5}$ km, we should observe big deviations between the spectroscopic profiles and the pure fluorescence profiles of the bands for the same regions. However, this does not seem to be the case, as for Burnham as well as for Ikeya the very large differences in the "temperature" of customary rotational motion are observed between CN and C_2 bands; these differences can only be explained in a satisfying way by the theory of fluorescence excitation. This argument is only qualitative, and we should calculate the fluorescence profile of the bands of these two comets and

compare it to the observed profiles before rejecting the hypothesis of an observed comet atmosphere with a radius of about 3,000 km in the case of Burnham.

CONCLUSION

The few preceding remarks do not pretend to give an exact explanation of the observed phenomena. We made them essentially to emphasize once more the importance of the thorough study of accurate photometric profiles as well as pure spectroscopic study. We realize perfectly by examining the profiles which are presented here that their discussion would be much easier if they covered a larger region of the head. With the cometary spectrophotometer, we shall /231 expect to establish the accurate photometric profile of various bands between 2,000 and 60,000 km for an average comet passing within 0.4 AU of the earth on the condition that we work at the Cassegrainian focus of the 193 cm telescope at the Haute Provence Observatory or at an equivalent telescope. We obviously hope that a comet as exceptional as Burnham, as regards its proximity to the earth and weakness of its continuum, will appear for us to observe in the years to come.

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